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Prediction of fatigue life of welded details in cable-stayed orthotropic steel deck bridges

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ABSTRACT

Welded details in cable-stayed orthotropic steel deck bridges are prone to fatigue damage and thus it is vital to fully understand their fatigue performance and effectively predict their fatigue life. In this study, fatigue life of welded joints is predicted based upon Miner's damage rule and the histogram of stress range frequency with consideration of traffic data. Stress level and the influence surface at welded joints of interest are computed using a mixed-dimensional finite element method. To accurately evaluate the traffic effect on fatigue performance, Monte Carlo simulation is used to generate the vehicle-induced stress history at critical welded joints, in such a way to develop the stress range frequency histogram. The rain-flow counting algorithm is utilized to determine the stress cycles while fatigue damage is computed by formula of Miner's rule. The proposed procedures for fatigue life prediction are implemented in a case study of a cable-stayed orthotropic steel deck bridge.

1. Introduction

Cable-stayed bridges have been gaining extensive attention due to their enhanced stiffness over suspension bridges for spans ranging from 200 to about 1000 m [1,2]. In order to effectively reduce the self-weight in such long-span bridges, orthotropic steel bridge deck that displays light weight and superior torsional stiffness is usually employed to substitute conventional reinforced concrete slab. A review of past literatures shows that orthotropic steel bridge decks are ever-increasingly used in the United States and other countries in recent decades [3–5]. In Asia, Japan is home to more than 250 orthotropic steel deck bridges [6]. Moreover, during a short period of time from 2000 to 2014, over 30 cable-stayed bridges with orthotropic deck systems were open to public in China [7,8].

A typical orthotropic steel bridge deck consists of a great number of welded joints. As clearly illustrated in Fig. 1, welding details of the orthotropic steel deck mainly include: (a) butt-welded joints in longitudinal ribs; (b) rib-to-deck welded joints; (c) rib-to-web (or diaphragm) joints; (d) butt-welded joints in the deck plate. These welded joints are vulnerable to fatigue-induced damage. Cracks often initiate from relatively small flaws due to welding in shop and/or construction site [9]. In addition, scallop cutout along the margin of the diaphragm also faces to fatigue failure [10]. In recent years, fatigue-prone cracks located at welded details, as shown in Fig. 2, have been reported in many orthotropic bridges in the United States [11], European countries [12], China [7,13] and other countries [14]. As a result, there is a highly demand for effective fatigue evaluation and fatigue life prediction of those welded details in cable-stayed orthotropic steel bridges, which is important to ensure bridge health and timely decision making in preservation activities.

Fatigue performance of a welded joint and its fatigue life prediction are usually affected by (a) welded details; (b) stress level and (c) traffic data. So far, much research has been conducted to better understand fatigue performance of orthotropic steel bridge decks under either quasi-static or traffic loadings [15–21]. Among them Connor and Fisher [16] performed full-scale laboratory testing on the rib-to-diaphragm joints. The procedure to measure and calculate fatigue stresses, which complies with the fatigue resistance specified in AASHTO LRFD Bridge Design Specifications [22], were introduced in detail. Their results demonstrated that the developed influence lines and/or surfaces are capable of capturing stress ranges. Similar analyses were conducted by Choi et al. [19] through both experimental and numerical study on the fatigue behavior of the rib-to-diaphragm joints, in which fatigue cracks were found to initiate from the weld toe. In addition, Xiao et al. [15] investigated the fatigue performance of the butt-welded joints in longitudinal ribs. They reported that the combined effects of incomplete weld penetration in butt welds and high truck traffic volume would

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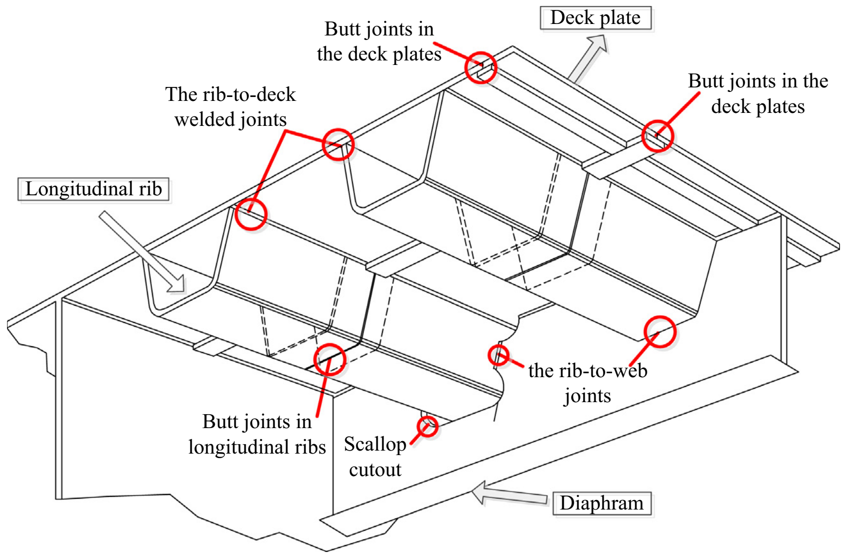

Fig. 1. Typical welded details in an orthotropic steel deck.

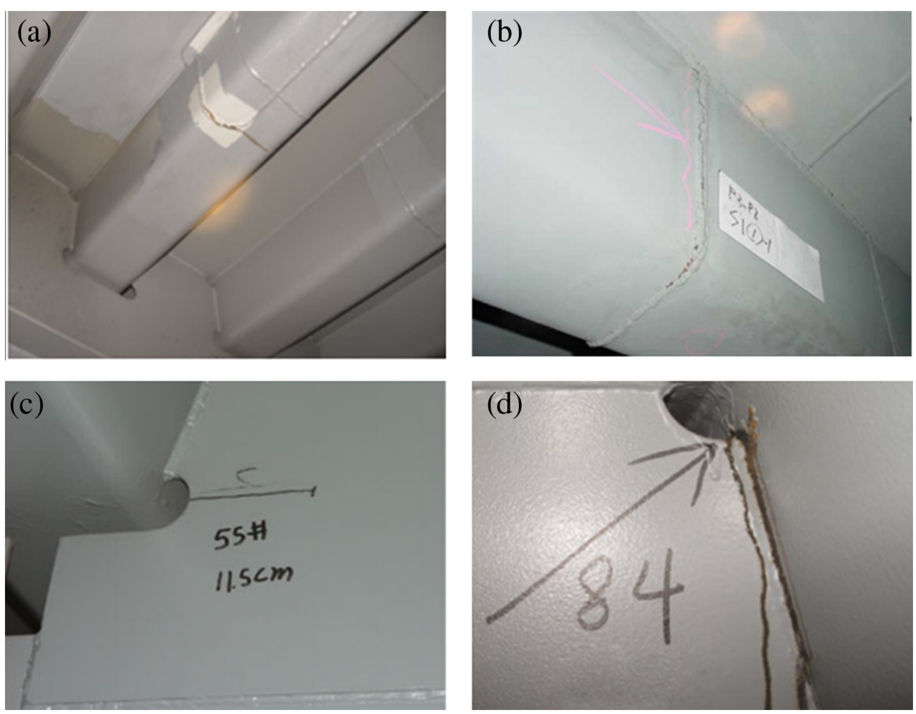

Fig. 2. Observed cracks in orthotropic steel decks located at: butt joints in longitudinal ribs (a) (from Ge and Xiang [7]) and (b) (from Xiao et al. [15]); scallop cutout (c) and rib to web joints (d).

eventually lead to fatigue cracks. Moreover, their following study on the rib-to-deck joints [20] revealed that fatigue strength was governed by fatigue cracks penetrating into the deck plate rather than that into the rib walls. Kolstein et al. [17] presented a review of typical fatigue details in orthotropic steel bridge decks and their corresponding testing programs in European and Asian countries. De Jong et al. [18] carried out numerical analysis to investigate the influence of traffic loading on the fatigue performance of welded details. Ya et al. [21] experimentally investigated fatigue performance of rib-to-deck joints with different weld penetration levels. As expected, 80% partial joint penetration was observed to be more vulnerable to fatigue cracks, and fatigue damage is more likely to occur at the weld root rather than the weld toe.

It is clear that most existing studies focused on certain welded joint(s) through either small-scale experiments or localized numerical simulation of orthotropic steel bridge decks. From a systematical standpoint, few attempts, however, were made to address fatigue performance of welded details in terms of the whole cable-stayed bridge. As a result, findings from these previous studies may not fully account for global fatigue response of various welded joints in an orthotropic steel bridge. Moreover, consider that the cable-stayed bridges are high order statically indeterminate, the simplified bridge deck system [23] cannot not capture the variations of responses when the cable forces are changing with different loading conditions, especially for the transverse contribution resolved from cable forces.